LASSO – Lunar Architecture Stochastic Simulator and Optimizer

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The Lunar Architecture Stochastic Simulator and Optimizer (LASSO) is a simulation-based capability, based upon discrete event simulation (DES), for evaluating and optimizing flight element options for lunar transportation architectures. This simulation capability improves the ability to rapidly measure cost, reliability, and schedule impacts of various top-level architecture decisions and individual elements within an architecture. The ability to probabilistically simulate and even optimize an overall transportation approach represents a significant enhancement over current deterministic analysis capabilities for top-level decision making. LASSO integrates a database of flight elements in Microsoft Excel® with architecture models in Rockwell Software's Arena®. The Arena models are further integrated into Phoenix Integration's ModelCenter® to allow optimization of the overall architecture by selecting various combinations of elements from the database. Sample results are presented for an expendable and a reusable lunar transportation architecture to illustrate the capabilities of LASSO for top-level decision making.

Nomenclature

CEV	=	Crew Exploration Vehicle
CES	=	Crew Escape System
DDTE	=	Design, Development, Test, and Evaluation
DES	=	Discrete Event Simulation
EELV	=	Evolved Expendable Launch Vehicle
GEM-FLO	=	Generic simulation Environment for Modeling Future Launch Operations
HLV	=	Heavy-lift Launch Vehicle
LASSO	=	Lunar Architecture Stochastic Simulator and Optimizer
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
LLO	=	Low Lunar Orbit
LOC	=	Loss of Crew
LOI	=	Lunar Orbit Insertion
LOM	=	Loss of Mission
LV	=	Launch Vehicle
OEC	=	Overall Evaluation Criterion
RLVSim	=	Reusable Launch Vehicle Simulation
TAT	=	Turn Around Time
TEI	=	Trans-Earth Injection
TFU	=	Theoretical First Unit
TLI	=	Trans-Lunar Injection
VBA	=	Visual Basic for Applications

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I. Introduction

IN the President's Vision for Space Exploration, President Bush called for a return to the Moon no later than the year 2020[1]. In order to do so, however, it is necessary to determine the best architecture and suite of vehicles within that architecture based on a variety of factors. Historically, many of these decisions have been made based on deterministic mass and performance-based analyses. Metrics such as cost, reliability, and the ability to meet a given campaign schedule have been considered later in the design process after many architecture and vehicle decisions have already been made, generally increasing the overall cost of the mission. Therefore, the ability to rapidly measure cost, reliability, and schedule impacts of top-level architecture and individual element decisions represents a significant improvement over the current deterministic analysis capabilities for top-level decision making. Allowing this knowledge to be brought forward in the design process will help to reduce the overall program costs down the road.

This capability is provided by LASSO, the Lunar Architecture Stochastic Simulator and Optimizer. Based upon discrete-event simulation (DES), LASSO is a simulation-based capability that provides the ability to probabilistically simulate and optimize an overall lunar transportation architecture in terms of cost, reliability, and adherence to a given program schedule. Discrete-event simulation (DES) as a modeling technique has existed for almost fifty years. Over the past two or three decades, with the improvement in computing power, simulation has become the most popular tool in operations research. Common examples of its use are in manufacturing, communications networks, transportation, and health-care delivery. Specifically, DES refers to computer models where changes occur only at distinct points in time, such as parts entering or leaving a manufacturing facility at specific times. Inherent to discrete-event simulation is the ability to model stochastic systems – that is, models with random inputs, such as random manufacturing times on a part. Therefore, the true power of DES lies in its ability to model a complex system and its underlying uncertainty, and to study the behavior of that system without having to build or make changes to the real thing.

Discrete-event simulation, however, is a fairly new tool to the space industry. Some work has begun, however, in using DES to model aspects of space missions, although it has generally been limited to modeling only ground operations. For example, NASA Kennedy Space Center has developed GEM-FLO (A Generic Simulation Environment for Modeling Future Launch Operations) using discrete-event simulation to model the launch operations processing for space transportation systems[2]. RLVSim (Reusable Launch Vehicle Simulation) was created at Georgia Tech, which is also a discrete-event simulation model for reusable launch vehicle ground operations.[3] LASSO, GEMFLO, and RLVSim were all created using Rockwell Software's Arena, a commercial DES program. LASSO is additionally combined with a database of vehicles in Excel and integrated into ModelCenter® to provide the capability to rapidly conduct design space exploration and optimization. In LASSO, the transportation-related aspects of lunar architectures are modeled end-to-end, from manufacturing, to integration and launch pad processes at the launch site, to all of the in-space segments and finally reentry and refurbishing of any reusable elements. Additionally, the model incorporates probabilistic simulations of cost, reliability, and processing times for each segment of the mission.

In this paper, the capabilities of LASSO are presented by examining two competing transportation architectures for lunar exploration: a highly reusable architecture and an expendable Apollo-style approach, each for a variety of launch vehicle scenarios. Sample results are presented for a variety of trade studies and figures of merit, including results for cost and reliability, the effect of limiting the available ground infrastructure, annual cost breakdowns, and the effect of varying the desired flight rate.

II. Lunar Architecture Stochastic Simulator and Optimizer

The Lunar Architecture Stochastic Simulator and Optimizer integrates three existing software programs to model, analyze and optimize lunar transportation architectures: Rockwell Software's Arena, Microsoft Excel, and Phoenix Integration's ModelCenter®. Arena is used to create full end-to-end models of lunar transportation architectures, including manufacturing of all the necessary transportation elements, payload and launch vehicle integration, launch, in-space propulsive segments, Earth re-entry, and turn-around processes for any reusable elements. Furthermore, the models include distributions on cost and time variables and a probability of failure for each launch, propulsive burn, and reentry. The Arena models are linked to Excel, which contains a database of the various elements within the architectures. These include launch vehicles, in-space propulsive stages, lunar landers, and crew exploration vehicles (CEVs). For each element, Excel contains pertinent metrics such as gross mass, propellant mass, payload capacity, cost, reliability, and cycle times. Finally, each architecture modeled in Arena is wrapped into ModelCenter® to provide the capability for design space exploration and optimization. This allows for optimizing both the overall architecture as well as individual vehicle choices to minimize overall program cost and risk and to maximize mission throughput.

A. Vehicle Database

The vehicle database in Microsoft Excel contains all of the pertinent data on each transportation element found in the lunar architecture, which is used by Arena in its architecture simulation. For each architecture simulation, three launch vehicles must be chosen, one type each for crew, cargo, and propellant (if a dedicated propellant launch is required to fuel vehicles on-orbit). Two types of in-space propulsive stages are chosen, one for the trans-lunar injection (TLI) and lunar orbit insertion (LOI) stages and one for the trans-Earth injection (TEI) stage. Finally, a lunar lander and a habitat element are chosen. Table 1 summarizes the different element types in the database, the elements available under each type, and their associated metrics. The database has been populated with a number of representative elements to illustrate the capability of LASSO, drawing from a combination of existing elements and paper studies. See Refs. 4-13 for additional information on each of the transportation elements. A countless number of transportation elements can be included in the LASSO simulation simply by added them to the database with their appropriate metrics.

Table 1. Transportation elements and associated metrics contained in LASSO vehicle database.

Element Type	Sub-Categories	Metrics
Launch Vehicles	Crew, Cargo, Propellant	Payload, DDTE, Reliability, and Lifetime
In-space Propulsive Stages	TLI/LOI, TEI	Payload, Dry Mass, Gross Mass, Propellant Mass, DDTE, TFU, Operations Costs (Fixed and Variable), Propellant Cost, Reliability, Manufacturing Time
Lunar Landers		Payload, Dry Mass, Gross Mass, Propellant Mass, DDTE, TFU, Operations Costs (Fixed and Variable), Propellant Cost, Reliability, Lifetime, Manufacturing Time, Built-in Habitat (yes or no)
Crewed Stages		Launch Mass (with CES), In-space Mass, DDTE, TFU, Operations Costs (Fixed and Variable), Reliability, Lifetime, Manufacturing Time, and TAT

In addition to containing all of the transportation elements available for the Arena simulation, the database also calculates the number of launches required per lunar mission based on the elements chosen. The number of TLI stages required is determined based on its payload capability and the mass of the remaining elements. Additionally, if the gross mass of the TLI stage(s) is larger than the payload capacity of the chosen launch vehicle, the TLI stage is launched dry and dedicated propellant launches are added to fuel the TLI on-orbit. The CEV must always launch on the chosen crew launch vehicle, along with the TEI stage if there is sufficient payload capability. For the remaining cargo elements, the optimal launch configuration is chosen as follows: first, if possible, the option with the minimum number of cargo launches subject to no dedicated propellant launches is chosen. If there are no feasible options without propellant launches, the option that first minimizes the number of cargo launches and then minimizes the number of propellant launches is chosen. Propellant launches are undesirable because they add the complexity of on-orbit refueling to the mission. If different logic is desired, this can also be easily changed by modifying this section of the Excel database.

B. Arena Lunar Architecture Models

The actual lunar architecture simulations are modeled in Rockwell Software's Arena. As aforementioned, the models span all transportation-related aspects of the architecture, including manufacturing, integration, launch, in-space segments, and turn-around processes. Fig. 1 shows a screen shot of the top-level Arena reusable lunar architecture model. All of the Arena modules are found in submodels to better organize the model, as well as to make for easy modularity for creating new architecture models. The teal colored box includes all of the submodels containing the model data flow. The plot on the top right illustrates the mission schedule in blue and the actual mission launch date in red. The key inputs to the model are found in the white boxes on the left, while the key outputs are found in the yellow boxes on the right. Additional data is compiled by Arena at the end of each simulation run as well as output to an Excel workbook for easy access and interface with ModelCenter®.

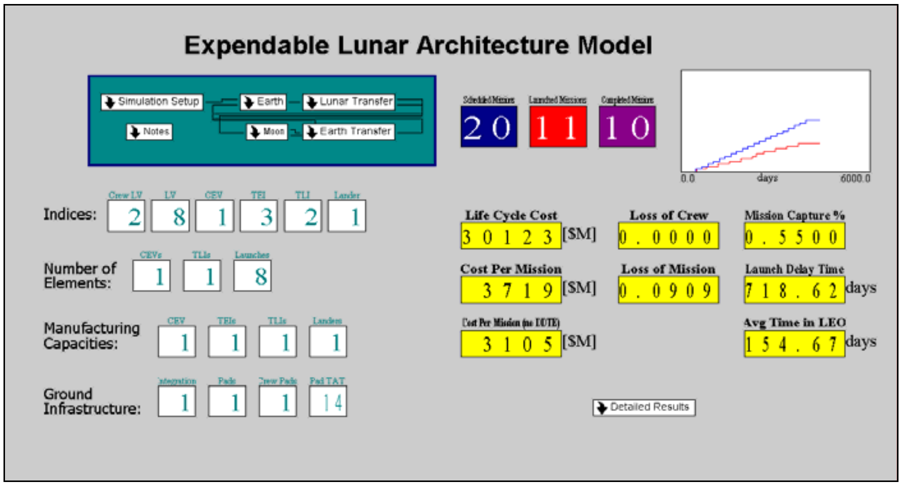


Figure 1. Screen Shot of Arena Reusable Lunar Architecture Model.

1. Inputs and Outputs

A detailed description of each of the inputs and outputs of the Arena models are found in Table 2 and Table 3. First, Table 2 describes each of the key inputs to the model. The user inputs the mean value for each variable, with the time and cost variables assigned triangular distributions within the Arena simulation. This allows for uncertainty in each of these variables to be modeled. The triangular distribution was chosen for two main reasons. First, this distribution is commonly used when the exact shape of the distribution is unknown, but good estimates of the minimum, mean, and maximum values are available. Additionally, it is particularly useful for this application because it is bounded, whereas the tails of the normal distribution extend to infinity in the positive and negative directions.

Table 2. Inputs to Arena Lunar Architecture Models.

Input	Description
Missions per Year	Number of scheduled lunar missions per year (can be a fractional value).
# Years	Number of years in lunar program (starting with first mission launch).
Vehicle Indices	Index number corresponding to an entry in the database for each element type (CEV, TLI, Lander, TEI, LV crew, LV cargo, and LV propellant).
Inventory Time	Time that elements should be delivered to inventory before integration is scheduled to begin.
Integration Time	Expected time for payload integration with launch vehicle.
Pad Time	Expected time for payload/launch vehicle stack to spend on launch pad prior to launch.
Pad TAT	Expected turn-around time of launch pad.
Investigation Time	Expected length of stand down time resulting from loss of crew event.
Manufacturing Capacities	Number of a particular element that can be built at one time (one variable each for CEV, TLI, TEI, and lander).
Integration Capacities	Number of launch vehicles that can be integrated with their payloads at a given time (one variable each for crew, cargo, and propellant).
Launch Pads	Number of launch pads available to that particular launch vehicle (one each for crew, cargo, and propellant).
Depot Capacity	Propellant capacity of propellant depot (if applicable).
Cost Lower Bound (%)	Lower bound on triangular distributions used for cost.
Cost Upper Bound (%)	Upper bound on triangular distributions used for cost.

Table 3. Key Outputs from Arena Lunar Architecture Models.

Output	Description
Life Cycle Cost	Total transportation-related program cost (includes DDTE, production, fixed and variable operations, launch, and propellant).
Cost per Mission	Life cycle cost divided by the number of launched missions.
Loss of Crew	Probability per mission that a loss of crew event occurs (number of loss of crew events divided by number of launched missions).
Loss of Mission	Probability per mission that a loss of mission event occurs (includes loss of crew events).
Mission Capture %	Percent of scheduled missions that are launched (missions cancelled due to stand down time do not count against capture %).
Launch Delay Time	Average time between scheduled launch date and actual first launch of that mission.
Time in LEO	Average time between first and last launch for a particular mission.
Bottleneck Statistics	Average waiting time in queues (manufacturing, integration, launch pads, turn-around processes).

Because many of the inputs into Arena are random variables, the outputs are also random. Therefore, running the simulation once does not provide meaningful information. Several replications must be run in order to get a distribution on each of the output variables of interest. According to the Central Limit Theorem, if a sufficient number of samples is taken, the mean of any random variable will be normally distributed, regardless of the distribution of that random variable. For this study, one hundred replications are conducted of each architecture simulation such that the outputs approximate a normal distribution. Arena automatically generates numerous outputs each time a simulation is run, but only a handful of these are of particular interest in evaluating an architecture. Table 3 lists the key figures of merit for the lunar architectures along with a description of each. For each output, the mean and standard deviation are recorded.

These outputs were defined with the intention of making each as independent as possible, so as not to be affected by changes in the other metrics. Life-cycle cost (LCC) includes all of the transportation-related costs modeled in LASSO for the entire program duration. Cost per mission was also chosen as a metric, because it reduces the dependence on capture percentage found in life-cycle cost. For example, if comparing two different architectures, one with 100% mission capture and one with 50% mission capture, the second will most likely have a lower life-cycle cost simply because fewer missions were launched. Cost per mission, however, divides the total life-cycle cost by the number of missions actually launched, which facilitates a more fair comparison between the two architectures. Loss of mission and loss of crew represent the probability that a particular mission will either fail or that the crew will be lost. Mission capture percentage is the percent of scheduled missions that actually launch. Even if there is a failure during the mission (including during launch), the mission still counts as having launched in calculating the capture percentage. The capture percentage statistic is therefore intended to measure how many missions can be achieved based on the throughput capability of the ground infrastructure. It is not intended to take reliability into account. Launch delay time and LEO time also pertain solely to ground infrastructure considerations, and are explained in Table 3.

The figures of merit, with the exception of the bottleneck statistics, make up the overall evaluation criterion (OEC) which is used to evaluate the overall merit of each architecture combination examined. Various figures of merit can be used, each with a particular weight assigned to it, depending on what criteria is most important to that particular simulation. The bottleneck statistics, however, are used to determine what the limiting ground infrastructure is if the mission capture percentage is less than 100%.

2. Lunar Architecture Concepts

For the purpose of illustrating the capabilities of LASSO, two representative lunar architectures were created in Arena: an expendable Apollo-style architecture and a next-generation highly reusable architecture. Each architecture has some common mission assumptions, as outlined below:

- Orbit characteristics:
  - LEO rendezvous orbit = 400 km × 28.5°
  - LLO rendezvous orbit = 100 km × 90° (polar orbit)

- Trajectory calculation[14]:
    - Time of Flight (LEO to LLO) = 3.5 days
    - TLI Delta-V = 3100 m/s
    - LOI/TEI Delta-V = 840 m/s
- Lunar mission specifications:
    - Number of crew = 4
    - Time on lunar surface = 4 days
    - Payload to lunar surface = 500 kg
    - Payload from lunar surface = 100 kg

Each of the entries in the database is based on the above assumptions. In order to change the assumptions, new vehicle elements could simply be added to the database.

The expendable architecture, shown in Fig. 2, consists of all expendable elements, as its name suggests. All the cargo elements are first launched into low Earth orbit on one or more cargo launch vehicles, depending on the payload capacity of the launch vehicle chosen. The crew is then launched in the CEV, along with the TEI stage, on a man-rated launch vehicle. All of these elements dock in Earth orbit, before beginning their transit to the Moon. Once in lunar orbit, the lunar lander ferries the crew to the lunar surface, while the CEV and TEI remain in lunar orbit. The chosen lander has a built-in habitat in the ascent stage, but if another surface habitat is desired, it can be pre-deployed (not currently modeled in Arena). The lander descent stage remains on the lunar surface, while the ascent stage then launches the crew back to lunar orbit, where it docks with the CEV and TEI. The crew transfers to the CEV, which travels back to Earth for a direct entry to the surface.

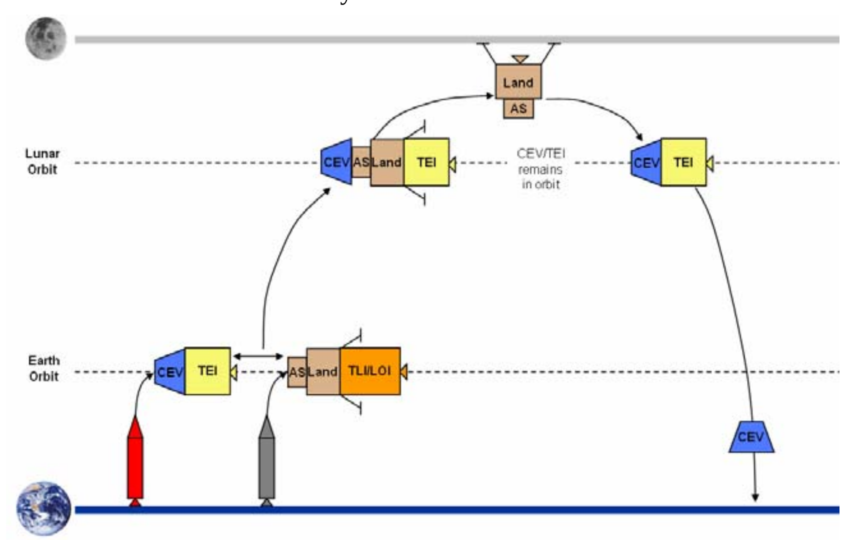


Figure 2. Diagram of Expendable Lunar Architecture.

The reusable architecture is shown in Fig. 3. The major difference in this architecture is the use of a reusable lunar lander and propellant depot in lunar orbit. Again, the cargo launches first on one or more launch vehicles, followed by the crew in the CEV, along with the TEI stage. The propellant depot and lander are pre-deployed along with a surface habitat if desired (the launch and costs associated with the surface habitat and fuel depot are not currently modeled). At the beginning of the simulation, an empty depot is assumed to already be in lunar orbit, and the lander is launched fully fueled before the first human lunar mission. Once the CEV/TEI and TLI have launched, they dock in Earth orbit and travel to the moon as a single stack. Upon arriving in lunar orbit, the lander ferries the CEV to the surface (the reusable lander does not have a built-in habitat), while the TEI remains in lunar orbit. Upon completion of the lunar mission, the lander carries the CEV back to lunar orbit, where it docks with the TEI for Earth-return. The lander refuels from the propellant depot and remains in lunar orbit until the next lunar mission is launched. The lander must be periodically replaced when it lifetime expires. Additionally, dedicated propellant launches to lunar orbit are required to periodically refill the depot with propellant.

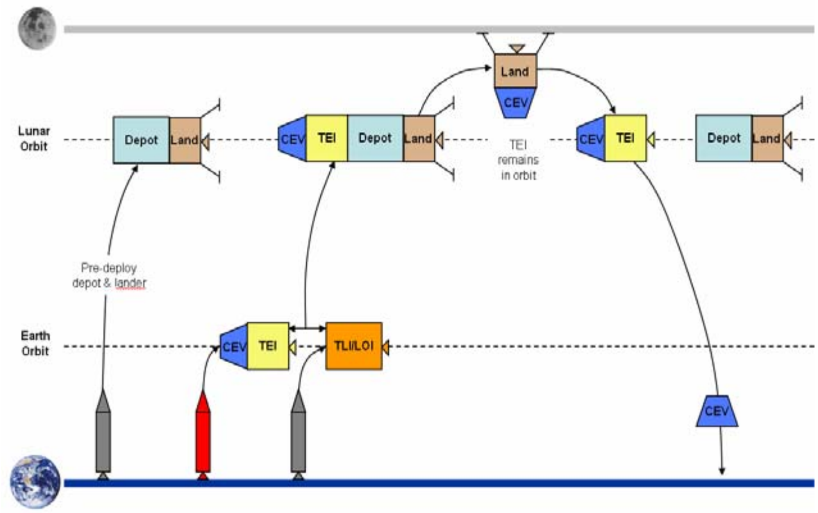


Figure 3. Diagram of Reusable Lunar Architecture.

3. Data Flow

Figure 4 illustrates a top-level flowchart of the data flow in the Arena models. The initial setup contains the interface with the Excel database as well as VBA code containing pertinent calculations. Although these calculations can be done using pre-existing Arena modules, they were significantly easier to implement in VBA. First, the VBA code calculates the expected number of reusable elements that will need to be built, with a minimum of three. Next, based on the number of missions desired per year and the manufacturing time for each element, it determines the day each element should begin manufacturing such that the mission will launch on time based on mean times for each process. It also calculates when each mission should begin integration such that it will launch on time. Finally, it checks if the mission is feasible for the given combination of elements, based on the following criteria:

- Is the lunar lander payload capacity sufficient to carry the CEV to the lunar surface (if applicable)?
- Is the crew launch vehicle payload sufficient to launch the CEV?
- Is the cargo launch vehicle payload sufficient to launch the single largest element?
- Is the TEI payload sufficient to carry the CEV to Earth?
- Is the TLI payload sufficient to carry the lander and the CEV/TEI?

If any of these conditions are violated, the simulation is immediately terminated. Arena also uses VBA code to transfer data to and from the Excel database.

The Demand submodel in Arena is responsible for handling the scheduling of the missions. It controls when each architecture element needs to begin manufacturing, when it needs to be removed from inventory to begin integration, and for the reusable architecture, when more propellant depot resupply launches are needed. The manufacturing submodel is straightforward. Each architecture element has its own manufacturing facility, each with a capacity and expected manufacturing time. Once manufacturing is complete, that element is stored in inventory. When a mission is scheduled to begin, the elements are sent to their correct launch facilities – between crew, cargo, and propellant – for integration and launch. Each type of launch vehicle has its own dedicated integration facility and launch pads, each with a user-defined capacity. For the reusable architecture, there is a separate submodel for launching the lander and propellant specifically for the lunar orbit propellant depot. These launches also have their own dedicated launch facilities. Although not shown in Fig. 4, after a launch takes place, the launch pad goes through a turn-around process before it can be used again for the next launch.

The in-space mission segments are also modeled as separate submodels. Each contains a probability of failure for each element that is used (TLI, TEI, lander, and CEV), along with times associated with each mission event (transit times, docking times, lunar surface time, etc.). Finally, upon successful Earth reentry, the expendable elements are disposed of, and any reusable elements go to refurbishing facilities before returning to inventory.

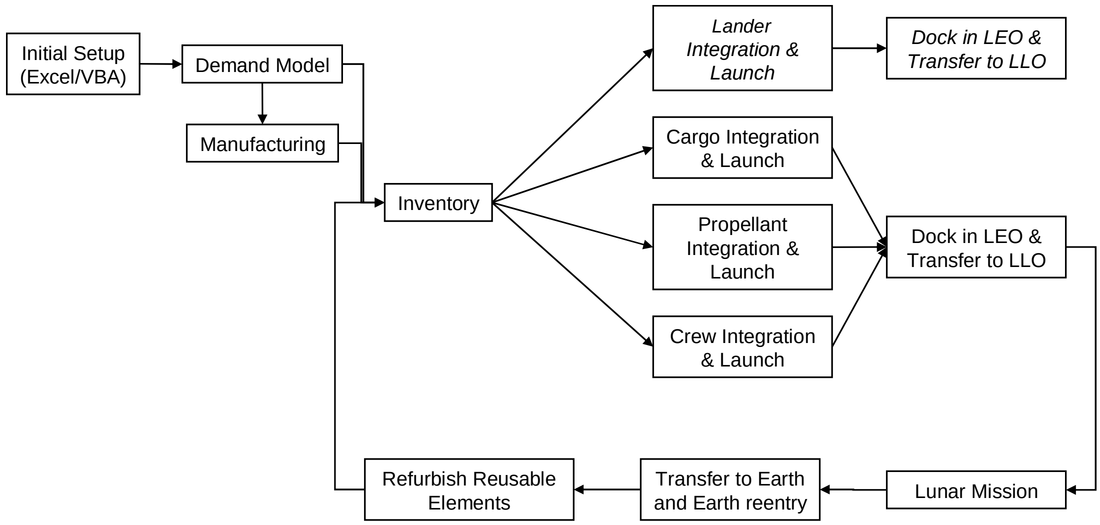


Figure 4. Top-Level Flowchart of Arena Models

4. Assumptions

In the lunar architecture models, certain assumptions are made about the system which are outlined here. Many of these assumptions were chosen to simplify the Arena models to conduct a proof-of-concept of the LASSO tool. They can easily be changed, however, by making modifications to the models. First, the LASSO architecture models model only the transportation-related elements along with their associated costs. This includes associated processes such as manufacturing, integration with the launch vehicle, and in-space segments, as well as costs such as DDTE, production, and operations. The transportation aspect of the lunar exploration program, however, comprises only a portion of the overall life-cycle cost of an actual program. In addition to the transportation elements, there are also costs associated with science payloads, technology development, precursor missions, etc. Therefore, the total cost reported by Arena can not be taken as the actual total cost of a lunar program.

In terms of the ground processes associated with conducting a lunar mission, LASSO models manufacturing, payload integration with the launch vehicle, time on the launch pad, and any turn-around processes required for reusable elements that return to Earth. It does not, however, include the costs associated with building additional launch pads or manufacturing facilities, for example. The user therefore must use some intuition to realize that, although missions may always launch on time when there are a hundred launch pads, it is not economically feasible to build an unlimited number of launch pads.

In terms of manufacturing, reusable elements are scheduled to begin manufacturing such that if everything goes according to schedule, they will be ready for launch on time. This includes a user-defined time when elements are supposed to arrive in inventory before a mission, which serves as a buffer if manufacturing does not run on schedule. All reusable elements, however, are built up-front, at the beginning of the program. The number of elements required to meet the mission demand is calculated, but a minimum of three reusable elements must be built. When a reusable element fails, one is removed from inventory and then an additional one is built to replace it if necessary. The model also incorporates “pay as you go” costs, which means that only elements used in a mission are paid for. Even if there were originally twenty missions scheduled, if only ten are launched because the program fell behind schedule, then the extra elements are not manufactured or paid for.

Crew, cargo, and propellant launches each have their own launch vehicle and dedicated facilities even if the same vehicle is chosen for cargo and propellant launches. Additionally, for the reusable architecture, a separate set of launch pads and integration facilities are used for launches required for depot resupply missions. For a lunar mission, the elements are always launched in the following order: cargo, propellant (if needed), crew. The crew does not launch until everything else has successfully reached orbit. If there is a launch failure of any cargo element, the mission is cancelled, and the crew, propellant, and any remaining cargo never launch. The elements that have not launched are returned to inventory. Any elements already in orbit, however, are lost. If a propellant launch fails, however, another one is simply launched to replace it. The amount of time elements must spend in lunar orbit, however, is not taken into consideration, although it is tracked as a variable. For example, if it takes a full year between when the first cargo element launches and when the crew launches, propellant boil-off or element lifetimes are not considered. Therefore, the user must examine the statistic representing the total time in low earth orbit to determine if that particular architecture choice and set of vehicles is feasible for a lunar mission.

There are several failures that can result in a loss of crew event. These include a crew launch vehicle failure where the abort is unsuccessful, a TLI stage failure where abort to Earth is unsuccessful, a lunar lander failure, a TEI stage failure, or a CEV reentry failure. It is important to note that smaller launch vehicles may not have sufficient payload mass to include a crew escape system, which results in having no abort option for launch. Whenever a loss of crew event occurs, a stand down time is initiated for an investigation, and all missions scheduled to launch during that time are cancelled. These cancelled missions, however, do not count against the mission capture percentage. Manufacturing for these missions is also cancelled, again so unnecessary costs are not incurred.

Finally, at the end of the scheduled program duration, no more missions may launch, but any mission in-flight at that time is allowed to be completed. For example, if a ten year program is desired, at the end of the tenth year of lunar missions, even if all the scheduled missions have not launched, the simulation is completed. If production has not begun for these missions, manufacturing costs are not incurred.

C. ModelCenter® Integration

Phoenix Integration's ModelCenter® is an environment that allows various software tools to be integrated together for design space exploration and optimization. The Arena lunar architecture models have been wrapped into ModelCenter® for this express purpose. Although not currently integrated with any other tools, it does provide the flexibility for the user to expand the functionality of LASSO by adding other disciplinary tools as desired. Using ModelCenter® also allows for parametric studies to be easily conducted. Certain variables can be varied and the results will be automatically generated for each case. This increases the speed of execution, since the user does not have to run each case individually in Arena and then record the results. Although Arena does have some limited design space exploration and optimization capability, it is not sufficient for the purposes of this study. For example, as will be seen in the results, the number of missions per year can be varied across a wide spectrum and the benefit of each architecture at different flight rates can be observed. Additionally, ModelCenter® with the DOT Optimizer allows for optimization of the overall architecture choice and elements within that architecture for a user-defined OEC.

III. Results

The two lunar transportation architectures presented above were modeled in Arena to illustrate the capabilities of LASSO. Several representative results will be presented here to illustrate the type of trade studies and design space exploration that would be conducted to evaluate the merits of each architecture under consideration. First, one of the distinguishing features of LASSO is the ability to probabilistically simulate a space transportation architecture, as opposed to the current deterministic modeling capabilities. Figure 5 illustrates two possible results for life-cycle cost (LCC). As expected, the results closely approximate a normal distribution, with the standard deviation of the output dependent on the variability of the inputs. The two dashed lines in the plot illustrate the location of the mean value of LCC for each architecture. If a deterministic decision-making approach were used, Architecture #1 would be chosen. While the mean value of LCC for Architecture #1 is less, its variability is much larger. As a result, there is a greater probability that the actual life-cycle cost could be much higher or much lower than for Architecture #2. By conducting a probabilistic simulation, Architecture #2 would most likely be chosen to reduce the variability in the results. Therefore, when analyzing the reusable and expendable lunar transportation architectures, 95% confidence values are used as opposed to the mean values. This captures the difference in variability between the options examined. LASSO, however, does allow the user to examine any confidence value desired.

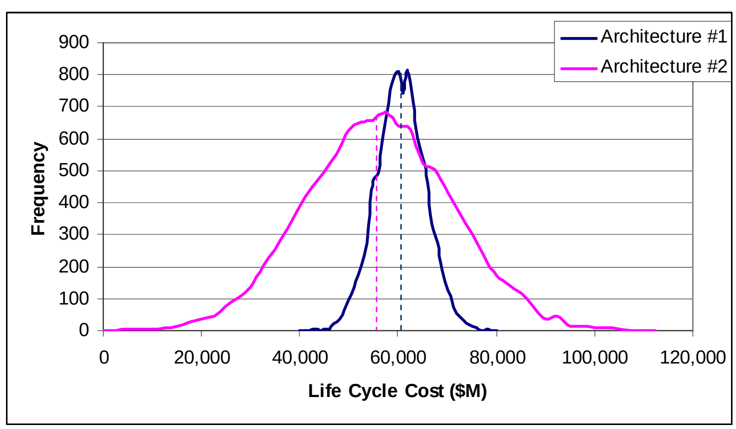


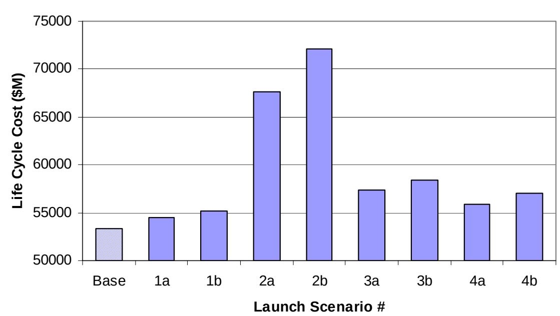
Figure 5: Sample LASSO results illustrating output distributions for life-cycle cost.

In order to illustrate how LASSO would be used to explore various architectures and individual vehicle combinations, a launch vehicle trade study was conducted. Table 4 lists the performance of the various launch vehicle examined for this study. Again, these are based on a combination of existing launch vehicles and paper studies. Both the reusable and expendable architectures were examined for the nine launch vehicle combinations. Several different results can be examined to aid in decision-making between the two architectures and between the various launch vehicles.

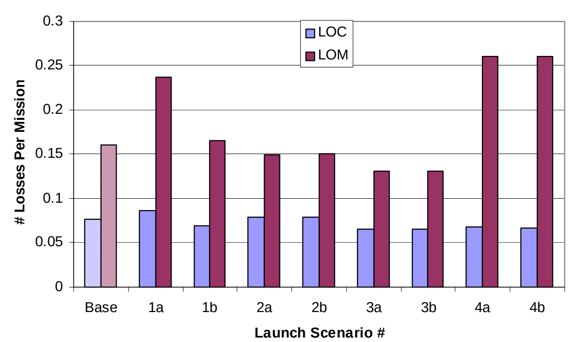
Table 4: Performance of launch vehicles examined for sample LASSO trade study.

	Launch Scenario	Crew L.V. Payload	Cargo L.V. Payload
	Baseline	23 mt	100 mt
1a	Existing EELVs	9 mt	23 mt
1b	Existing EELVs	23 mt	23 mt
2a	Evolved EELVs	23 mt	40 mt
2b	Evolved EELVs	23 mt	70 mt
3a	HLVs	35 mt	100 mt
3b	HLVs	35 mt	140 mt
4a	Shuttle-Derived	20 mt	77 mt
4b	Shuttle-Derived	34 mt	77 mt

First, the life-cycle cost and reliability for each architecture and launch vehicle combination can be examined, based on an unlimited manufacturing capacity, number of integration facilities, number of launch pads, and vehicle and launch pad turn-around facilities. Every scheduled mission will therefore launch on time, thereby preventing delays from influencing the cost and reliability results. Figure 6a plots the LCC and Fig. 6b plots the LOM and LOC probabilities for the expendable architecture. As explained, 95% confidence values are presented, to account for the different variabilities between the options examined. As can be seen from the cost results, two of the launch vehicle options are significantly more expensive than the remaining alternatives. Based on cost alone, these two would clearly be ruled out, whereas the baseline, option 1a, or option 1b would likely be chosen. When reliability is examined, however, these three options actually have a worse loss of mission probability than options 2a and 2b which did so poorly in the cost category. Furthermore, the last two launch vehicle options did very poorly in reliability, while they were fairly competitive in the cost category.



a) Life cycle cost ($M).



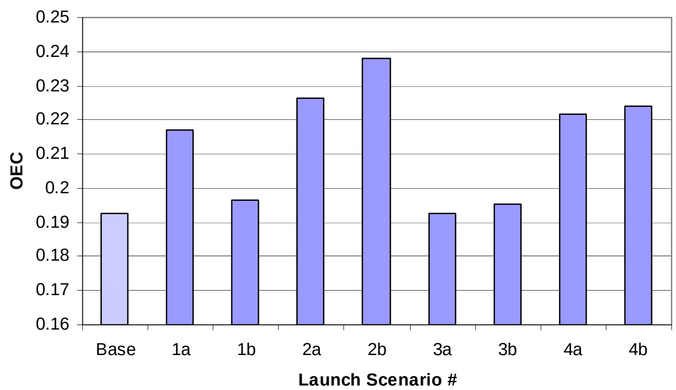
b) Number of losses per mission.

Figure 6: Results for expendable lunar transportation architecture launch vehicle trade study, based on unlimited ground infrastructure.

Therefore, in addition to examining single output categories, LASSO enables the analyst to build an overall evaluation criterion by assigning different weightings on the various categories. In this example, two categories are being examined – cost and reliability – but more can easily be added. The OEC, shown for each launch vehicle option in Fig. 7, is constructed as shown in Eq. (1). A weighting is assigned to each figure of merit, with the sum of the weightings required to equal 100%. Each value is also normalized such that each different figure of merit falls in the same range across all of the options being examined.

$$OEC = \%_{\cos t} * \left(\frac{LCC}{200000} \right) + \%_{rel} * \left(\tfrac{1}{2} LOC + \tfrac{1}{2} LOM \right) \tag{1}$$

Figure 7 plots the OEC for the expendable architecture for the weightings on both cost and reliability ($\%_{cost}$ and $\%_{rel}$) equal to 50%. As can be seen from the plot, some of the launch vehicle options that appeared favorable from a cost standpoint become much less attractive when reliability is also examined. Additionally, the table in Fig. 7 ranks each of the launch vehicle options for the expendable architecture based on three different weightings of the OEC: 100% cost, 100% reliability, and 50%-50% cost-reliability. Depending on whether cost or reliability is more important to a lunar exploration program, a different set of launch vehicles would be chosen. Although this is a fairly simple example illustrating only cost and reliability for the expendable architecture, it stresses the importance of incorporating multiple figures of merit as well as examining different weighting scenarios to determine which architecture is the best across the board.



Launch Option	Rankings Cost	Rankings Reliability	Rankings 50-50
Baseline	1	6	**1**
1a	2	7	**5**
1b	3	5	**4**
2a	8	3	**8**
2b	9	4	**9**
3a	6	1	**2**
3b	7	2	**3**
4a	4	9	**6**
4b	5	8	**7**

Figure 7: Overall evaluation criterion for expendable lunar transportation architecture.

In addition to exploring various architectures and vehicles, the effect on limiting the available ground infrastructure can be studied for a particular architecture. The above cost and reliability results are based on unlimited infrastructure, such that the mission capture rate is always 100%. If this infrastructure is limited, however, different launch vehicle combinations will perform better in terms of meeting the lunar mission demand. As explained earlier in Table 3, several figures of merit can be used in LASSO to characterize the effect of limited ground infrastructure. These include capture percentage, average launch delay, and time of elements in Earth orbit. As an example, Fig. 8 plots the capture percentage for the same launch vehicle combinations for the expendable architecture. This assumes a limited set of ground infrastructure, such that all of the manufacturing and integration facilities have a capacity of one, and there is only one launch pad for each type of launch

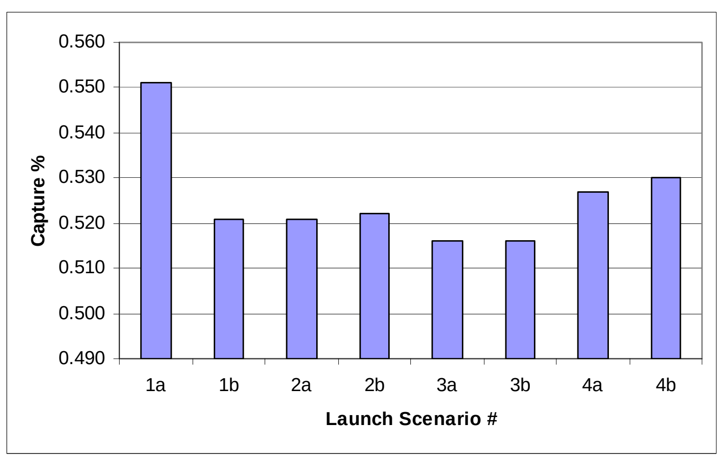


Figure 8: Mission capture percentage for expendable architecture based on limited ground infrastructure.

vehicle. For two lunar missions per year, this set of ground infrastructure is not sufficient to reach 100% mission capture for any of the options plotted. Some of the options, however, did result in higher values of the mission capture percentage. LASSO can also be used to determine the minimum set of ground infrastructure required to reach a desired value of any of the scheduling figures of merit. For example, for launch option 3a, the minimum ground infrastructure to achieve 100% mission capture is as follows: one launch pad for each type of launch vehicle, all integration facilities with a capacity of one, TLI manufacturing facility with a capacity of one, and CEV, lander, and TEI manufacturing facilities with capacities of two.

In the above launch vehicle trade study results, cost results were presented for undiscounted life-cycle cost. Another important factor, however, is the annual funding required, since a program is generally allocated a given budget on a yearly basis, not a lump sum that can be spent each year as needed. Using LASSO, architectures can also be compared in terms of yearly spending. The results here assume that DDTE costs are spread evenly across the first five years of the program. Production begins the following year, with costs assigned to the year in which production of a particular element starts. Over the ten years where missions are flown, costs are broken down into production, launch, and operations costs. Finally, there are no launches in the last year of the program, but fixed operations costs are still incurred. All of the costs shown are in 2005 dollars. Fig. 9 plots the annual transportation-related costs for two of the launch vehicle options for the expendable architecture. Depending on the funding available, the choice of architecture could be heavily influenced by the results shown in this plot. The baseline launch vehicle scenario has lower costs once lunar missions begin, but requires higher costs up-front, while the existing EELV option requires much lower costs up-front but incurs higher mission costs down the road.

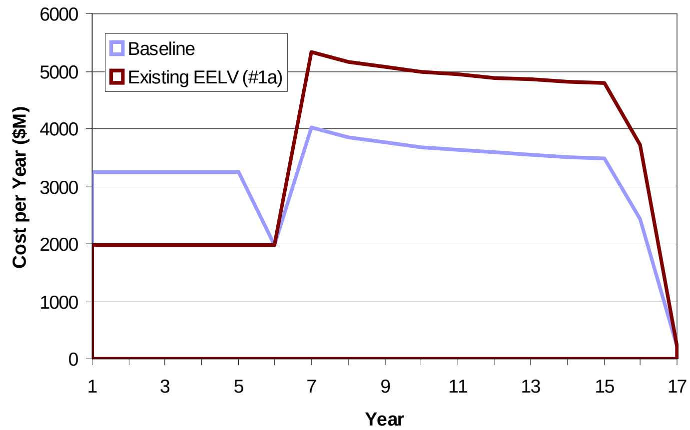


Figure 9: Annual transportation-related program costs for two launch options for the expendable architecture.

All of the results shown thus far have been for the expendable lunar architecture. Comparing architectures is of course a key feature of LASSO. The final result shown will illustrate one of the many ways that different architectures can be compared. One of the other variables of interest that can be varied is the desired flight rate per year. While a program may initially intend to fly at a certain flight rate, budget cuts or mission success can decrease or increase the planned rate. Therefore, an architecture that does well across a wide range of flight rates is favorable. Figure 10 plots the cost-per-mission for the baseline launch vehicle scenarios for the expendable and reusable architectures as a function of annual flight rate. Other figures of merit are also of particular interest, such as life-cycle cost, mission capture percentage, and maximum achievable missions per year. Two key results deserve to be pointed out from Fig. 10, however. First, for the baseline launch vehicle, the cost-per-mission of the expendable architecture is consistently less than for the reusable architecture. Second, for both architectures, at least two missions must

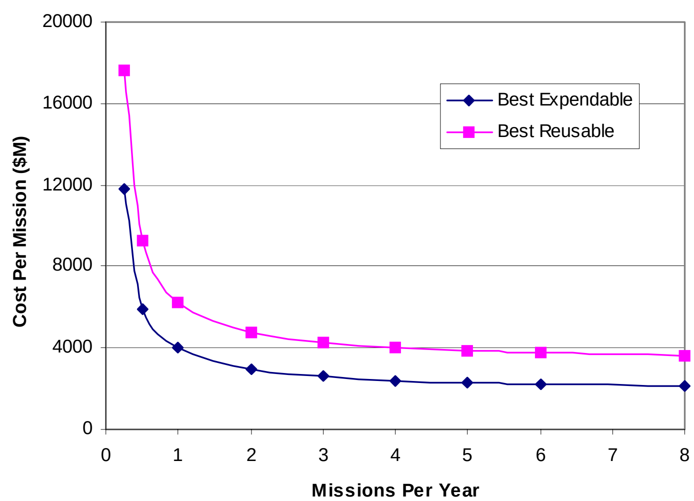


Figure 10: Cost-per-mission as a function of flight rate for the baseline launch vehicle option for the expendable and reusable architectures.

be flown per year for a ten-year program in order for each mission to be cost effective.

IV. Conclusions

The results presented above are intended to be representative of the capability of LASSO to evaluate and optimize lunar transportation architectures for a number of different figures of merit, although they only represent a small subset of the full capability of this new simulation approach. For example, additional trade studies can be conducted on the individual vehicle elements, simply by running the LASSO simulation with different elements in the database. Additional flight elements can easily be added by adding new line items to the Excel database. Furthermore, the modularity of the Arena architecture models allows for changes to be quickly and easily made to the current lunar transportation architectures or for new architecture to be built using the basic pieces of the current models. Parametric studies can be conducted on any of the inputs listed in Table 2 to examine the effects on any of the figures of merit listed in Table 3. Additional inputs and outputs can also be added to LASSO by modifying the Arena models. Many of these additional trades on the reusable and expendable lunar transportation architectures were conducted under this research grant. For more detailed results on the architecture study, refer to Ref. 15.

LASSO also allows for probabilistic simulation of these transportation architectures, which accounts for uncertainty present at the early stages of the decision-making process. Costs, reliability, and process times can only be estimated during conceptual design; therefore, the variability of the results must be taken into account when choosing an optimal transportation approach. This was illustrated in Fig. 5.

These distinguishing capabilities of LASSO provide the decision-maker additional information in choosing an overall lunar transportation approach. Previously, cost, reliability, and ability to adhere to a given program schedule were rarely considered early in the design process, which often led to cost and schedule overruns later in the process. For example, Fig. 9 illustrates the need to consider annual funding in the overall design process. If the architecture with the higher up-front costs were chosen, more money could actually be saved overall for a long-term program. If only up-front costs were considered, the other architecture would likely have been chosen, which would result in higher costs down the road. Additionally, the available ground infrastructure must be considered, as is addressed in Fig. 8. Building more manufacturing and integration facilities and more launch pads can also cause cost and schedule overruns if these aspects are not considered early on in the decision-making process.

The capabilities provided by LASSO – the ability to examine non-performance based figure of merit in a probabilistic simulation environment – are therefore critical to establishing a cost-effective and sustainable human lunar exploration program. If only performance metrics are used during the conceptual stage of the design process, a program can run into budget and schedule problems down the road, when they will be more difficult and expensive to correct. Therefore the capability to evaluate space exploration architectures based on cost, reliability, and scheduling figures of merit will be essential to successfully implementing the President's Vision for Space Exploration through the next several decades.

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